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EXPLORATORY STUDIES ON MODIFIED ALUMINIDE COATINGS FOR LOW CARBON AND STAINLESS STEELS

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16. Abstract

Five modified aluminide coatings were applied to 304 stainless steel and low carbon steel. The coated specimens were cyclically furnace oxidation tested for up to 100 hours at 2000° F (1366 K) and 600 hours at 1800° F (1255 K). The coatings were evaluated based on visual appearance after oxidation, metallographic examination, and X-ray diffraction analyses. Following furnace oxidation tests, a Ni-Cr-Al coating on 304 stainless steel was selected for further study in an automotive thermal reactor test. The results of this testing thus far (166 cycles), show good oxidation resistance in an automotive exhaust environment.

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SUMMARY

An aluminide coating, two chromium-aluminum (one and two step processes) coatings, a flame sprayed nickel - 20 aluminum plus aluminum diffusion coating, and a flame sprayed nickel - 20 chromium plus aluminum diffusion coating were applied to both 304 stainless steel and to low carbon steel. Cyclic furnace oxidation of these specimens was carried out in a multitube furnace for up to 100 hours at 2000° F (1366 K) and 600 hours at 1800° F (1255 K) in flowing air. The coated low carbon steel specimens had short lives at 2000° F (1366 K) making them unacceptable for applications such as automotive thermal reactors. The coated 304 stainless steel specimens had much better oxidation resistance than the coated low carbon steel specimens.

Following furnace oxidation testing one system, the Ni-Cr-Al coating on 304 stainless steel, was selected for automotive thermal reactor testing. Preliminary data indicate that on the basis of oxidation resistance this combination is a good candidate for a possible automobile thermal reactor application.

INTRODUCTION

The automotive internal combustion engine exhausts carbon monoxide (CO), carbon dioxide (CO_2), nitrogen dioxide (NO_2), unburned hydrocarbons, etc., into the atmosphere. Federal regulations have now been imposed which set progressively smaller allowable engine exhaust levels for these combustion products. Relatively minor changes in engine construction and operation were initially required to meet these requirements. However, to meet the projected 1975 Federal requirements, exhaust converters or reactors appear necessary (ref. 1).

One approach to minimize unwanted exhaust products is by the use of a thermal reactor. This device would replace the exhaust manifold. By the introduction of

secondary air it would serve as a container in which complete combustion of unburned hydrocarbons and CO could occur. To achieve the desired results, the critical components of a thermal reactor normally must operate at temperatures up to 1900° F (1311 K) with the possibility of reaching 2300° F (1533 K) if a spark-out occurs (refs. 1 and 2). Reactor lives of 2000 hours or more (50 000 miles at an average speed of 25 miles per hour) are desired. Under these severe temperature, exhaust atmosphere, and life conditions, oxidation corrosion, and erosion, as well as chemical attack by lead and sulfur compounds, are significant. One possible answer to such problems is the use of protective coatings on the structural metals used in the thermal reactor (refs. 1 to 3).

Because of the intended automotive application these reactors would need to be mass produced at the minimum possible cost. The low cost and moderately high temperature strengths of low alloy steels make them interesting candidate materials. Such materials, however, are rapidly degraded by the environmental conditions found in a thermal reactor (ref. 2). For this reason, an exploratory effort was conducted at Lewis to determine if coating technology could be developed to protect low-cost low-alloy steels for thermal reactor parts.

Five coatings were applied to low carbon and 304 stainless steel substrates. These coatings included an aluminum diffusion coating (Al); a one and a two step chromium-aluminum diffusion coating (Al, Cr and Cr+Al); a flame sprayed nickel-aluminum coating, which was subsequently aluminum diffusion coated (Ni-Al/Al); and a flame sprayed nickel-chromium coating, which was subsequently aluminum diffusion coated (Ni-Cr/Al). The first four coating systems were deposited at Lewis to provide a basis for comparison with similar aluminide coatings on more highly alloyed steels (ref. 2). The last system, Ni-Cr/Al, was an effort to extend the protection ability of coatings for 304 stainless steel substrates.

All of these coatings were oxidation tested at 2000° F (1366 K) in a multitube furnace for up to five 20-hour cycles. Following this preliminary screening, air oxidation testing was carried out at 1800° F (1255 K), in 20-hour cycles for 600 hours. Weight change, metallographic, visual, and X-ray diffraction analyses were used to evaluate the test results. Also, a limited amount of testing was recently conducted in an experimental automotive thermal reactor.

SUBSTRATE PREPARATION

The substrates used in this program were austenitic 304 stainless steel (Fe-18Cr-8Ni-0.008C) and low carbon, hot rolled sheet steel (Fe-0.1C). Furnace test specimens (3/4 by $1\frac{1}{2}$ in. (1.90 by 3.81 cm)) and automotive reactor test specimens (1 by 2 in. (2.54 by 5.08 cm)) were sheared from 1/16 inch (1.58-mm) thick sheet stock. To assure

surface and edge radius uniformity, the specimens were ball milled in a ceramic mill with number 36 alumina grit and water. After milling, each specimen was vapor blasted with -100 mesh alumina, degreased, and ultrasonically cleaned in trichloroethylene. Each specimen was then weighed, measured, and given a final vapor degreasing in trichloroethylene.

COATING PROCESSES

Aluminum Diffusion Coating (Al)

The aluminum diffusion coating was applied by pack cementation. The pack mixture was: 96 percent alumina, 2 percent aluminum, 1 percent sodium chloride, and 1 percent ammonium bifluoride by weight. The pack was placed in a retort and heated to $1600^{\circ} \pm 10^{\circ}$ F (1144 K) for 16 hours with a flowing argon (0.028 m^3/hr) atmosphere. Table I shows the average weight gains for each substrate and the phases determined to be present in the resulting coating from X-ray diffraction data.

Chromium-Aluminum Diffusion Coatings (Al, Cr) and (Cr+Al)

Two chromium-aluminum diffusion coatings were applied. The first diffusion coating involved the simultaneous applications of chromium and aluminum by the use of a multielement pack cementation technique (Al, Cr). The second diffusion coating was a two step process (Cr+Al). Here, chromium was first applied by vacuum pack cementation. The pack consisted of chromium powder with 1 percent (by weight) chromium chloride. The pack was placed in a retort and heated in a vacuum furnace to 1600° F (1144 K) for 5 hours. An aluminum diffusion coating was then applied over the chromium rich layer using the procedure previously described. Table I shows the average weight gained by each coating process on each substrate as well as the phases determined from X-ray diffraction data to be present in each coating.

Flame Sprayed Coatings

Nickel-aluminum/aluminum (Ni-Al/Al). - Specimens from each substrate were flame sprayed with 80 nickel-20 aluminum wire. After a 5 mil (127 μm) thick coating was deposited, the specimens were aluminum diffusion coated as previously described. The average weights gained after flame spraying and after aluminum diffusion coating

for both substrates are shown in table I. The phases determined from X-ray diffraction data to be present in the coating after aluminum diffusion coating are also shown in table I.

Nickel-chromium/aluminum (Ni-Cr/Al). - A 5-mil (127-μm) thick coating of a nickel - 20-chromium alloy powder was applied by flame spraying. Following flame spraying, the specimens were aluminum diffusion coated as previously described. The phases present in the coating after aluminum diffusion coating as determined from X-ray diffraction data and the average weight gained following flame spraying and following aluminum diffusion coating are presented in table I.

MATERIALS TESTING AND EVALUATION

All cyclic oxidation tests were carried out in a horizontal multitube furnace. Test conditions ranged from up to 100 hours at 2000° $\pm$10° F (1366 K) to 600 hours at 1800° $\pm$10° F (1255 K). Each specimen was placed on a high purity recrystalized alumina boat. One boat was placed in each tube of the multitube furnace during testing. Air was passed over the specimens at the rate of approximately 2 cubic feet per hour (0.028 m^3/hr). The cycles consisted of 20 hours at the test temperature followed by cooling to room temperature. While at room temperature, the specimens were lightly brushed to remove any loose oxide scale and weighed to $\pm$0.05 milligram per square centimeter accuracy.

Test specimens were exposed in a thermal reactor modified as shown schematically in figure 1. The test specimens were mounted on a rack directly under the exhaust ports and as such were exposed to the worst possible temperature, erosion, and corrosion conditions expected in a thermal reactor (ref. 2). Metal temperature was measured by thermocouples mounted on adjacent uncoated test specimens.

A 472 cubic inch (7741 cm^3) displacement, production V8 engine was used with standard air injection and carburetion. Leaded gasoline was used as fuel. The engine was operated to provide test specimen temperature cycles of 10 minutes at a peak temperature of 1900° F (1311 K) and 5 minutes at 1200° F (922 K) and repeat. Intermittently, the reactor was cooled to room temperature for inspection and specimen weighing. Variation in metal temperatures through the test was $\pm$40° F ($\pm$22 K).

Samples for X-ray diffraction were obtained by lightly grinding the two large flat surfaces of representative specimens with a small diamond cutting wheel. The powder X-ray diffraction patters were obtained by Debye-Scherrer camera techniques using chromium k_{α} radiation with a vanadium filter.

The metallographic specimens were mounted in an epoxy resin based material. The samples were mechanically polished through 1-micrometer diamond powder then etched

with the following solution: 20 parts water, 50 parts glycerine, 30 parts hydrochloric acid, 10 parts nitric acid, and 1 part hydrofluoric acid.

RESULTS AND DISCUSSION

Low Carbon Steels

The results of 2000° F (1366 K) furnace test evaluations of all coating systems on low carbon steel indicated that there was extensive oxidation and substrate metal loss. The final weight changes after testing for two 20-hour cycles at 2000° F (1366 K) are shown in table II. Figure 2 contains representative photomicrographs of the Ni-Cr/Al coating (later shown to be one of the most protective coatings on 304 stainless steel) in the as-coated condition and after exposure at 2000° F(1366 K). The weight losses shown in table II are very large indicating that the coating had been consumed and that the substrate material had begun to oxidize. Extensive interdiffusion and oxidation between the coating and the substrate is examplified in figure 2. In view of these observations it was concluded that none of the coating systems tested on low carbon steel could approach the time and temperature requirements of a thermal reactor. Therefore, no further studies were made of these coatings on low carbon steel.

304 Stainless Steel

The behavior in cyclic furnace oxidation tests of the five coatings deposited on 304 stainless steel is summarized in table II. Figure 3 shows cross sectional photomicrographs of the Al; Cr; and the Cr+Al coatings on 304 stainless steel in the as-coated condition and after testing at 2000° F (1366 K) and 1800° F (1255 K). Figures 4 and 5 contain cross sectional photomicrographs of the Ni-Al/Al and the Ni-Cr/Al systems, respectively, on 304 stainless steel in these same conditions. The major observations that can be made from the data in this table and from the photomicrographs in these figures are discussed briefly in the following paragraphs.

2000° F (1366 K) screening tests. - The coated 304 stainless steel specimens showed much more oxidation resistance than did the low carbon steel specimens at this temperature. Of the five coating systems tested only the Al, Cr system on 304 stainless steel did not have sufficiently low weight change (see in table II) to justify further testing. The oxidized Ni-Al/Al and the oxidized Ni-Cr/Al specimens showed small net weight gains. The Al coating lost only a very small amount of weight. The Ni-Cr/Al coated specimen was only tested for 80 hours at 2000° F (1366 K) because of the occurence of several edge failures. The Cr+Al coating experienced general surface failure after 80

hours (four cycles) of testing. Visually, the aluminum coated specimen appeared to be somewhat better than the other coatings in these 2000° F (1366 K) screening tests.

The phases in these coatings after oxidation testing were determined from X-ray diffraction data and are shown in table II. The aluminum diffusion coating and the Ni-Cr/Al coating on 304 stainless steel after testing have an Al_2O_3 and a spinel (a_o = 8.35 A) surface phase. The Ni-Al/Al coating on 304 stainless steel has Al_2O_3 and nickel aluminide phases on the surface.

Figures 3 to 5 show that in these systems, inward diffusion of coating constituents was extensive. However, in all cases the diffusion was less than observed on low carbon steel. From consideration of X-ray diffraction and metallographic data the authors believe that the high aluminum concentrations originally present in these systems (i.e., Ni_2Al_3, etc.) have, through interdiffusion, produced a thick metal aluminide (MAl) zone containing large columnar grains beneath the surface. This zone is a reservoir for Al and appears to serve as a barrier against grain boundary oxidation in the 304 stainless steel.

Compared with the coatings investigated on Fe-20Cr-32Ni in reference 2 (Al hot dipped, Cr+Al, and plasma sprayed Ni-Al followed by aluminum hot dipping) pack aluminization, Cr+Al multistep packs, and Ni-Al/Al coatings in this study on the lower alloy content 304 stainless steel were similarly protective.

1800° F (1255 K) - 600 hour testing. - All of the coatings, with the exception of the one step chromium-aluminum coating, were furnace tested on 304 stainless steel at 1800° F (1255 K) for up to 600 hours. The weight change data gathered throughout the testing cycles are also summarized in table II. Figure 6 shows these data in graphical form. With the exception of the Cr+Al coating, all systems showed small weight gains. From the weight change data, both the flame sprayed and the aluminum diffusion coated coatings (Ni-Al/Al and Ni-Cr/Al) and the unmodified aluminum diffusion coatings showed good oxidation resistance. The Cr+Al coating showed good protection for about 300 hours but then began to lose weight.

The surfaces of all the flame sprayed and aluminum diffusion coated specimens and the unmodified aluminum diffusion coating appeared to be well protected all during the 600 hours of testing at 1800° F (1255 K). Very little spalling was noticed on any of these coatings.

The X-ray diffraction analyses of the tested coating surfaces are presented in table II. From these X-ray diffraction data, all the coatings appear to have been protective. The major phase present in all cases was Al_2O_3.

Photographs of the aluminum diffusion coated and Cr+Al coated specimens are shown in figure 3. The aluminum diffusion coated specimen exhibited extensive columnar grain growth of an MAL phase due to interdiffusion of coating material. Oxidation of this specimen seems to have concentrated near the original coating-substrate interface with

some internal oxidation taking place. The Cr+Al coated specimen appears to have undergone much less columnar MAl grain growth. However, large voids are present throughout the portion of the coating above the MAl region.

The photographs of the Ni-Al/Al and Ni-Cr/Al coated specimens are shown in figures 4 and 5, respectively. For both systems a larger MAl phase region is present in the tested specimens. This could indicate a large Al reservoir in the tested specimens. Large voids appear to have agglomerated along the original substrate-coating interface of the tested Ni-Al/Al specimen. Less oxidation of this layer is seen in the tested Ni-Cr/Al coated specimen.

The results of oxidation testing of coated 304 stainless steel indicated that the Ni-Cr/Al coating on 304 stainless steel had the maximum potential to meet the time-temperature requirements set forth in the INTRODUCTION.[1] The coating showed good weight stability, good coating preservation, and metallographically was the most stable after 600 hours of cyclic oxidation at 1800° F (1255 K). During 2000° F (1366 K) testing this coating performed equally as well. (While edge failures were noted during 2000° F (1366 K) testing they were attributed to processing and the main body of the specimen was relatively sound metallographically and well protected.) For all of these reasons it was desired to further test Ni-Cr/Al on 304 stainless steel.

Preliminary Automotive Thermal Reactor Test Results

Using the 1900° - 1200° - 1900° F (1311 - 922 - 1311 K) cycle previously described, with intermediate cooldowns to room temperature, preliminary tests of the Ni-Cr/Al coating on 304 stainless steel have been made on test specimens in an experimental automotive thermal reactor which is connected to a high performance 472-cubic-inch (7741 cm^3) V8 automobile engine. The weight change data (unpublished; R. E. Oldrieve, Lewis Research Center) obtained are presented in graphical form in figure 7. The coating initially gained weight in forming a protective oxide layer and then appeared to have experienced little further weight change. Visually the surfaces of the coated specimen after testing 166 cycles were almost unchanged from the as-coated condition. The uncoated 304 stainless steel lost weight rapidly indicating severe oxidation attack and oxide spalling. The weight change performance of several high nickel alloys (data not reported

[1]This decision was based on the observation of lines of porosity, approximately 25 to 50 μm below the surface, in all of the other promising systems. Such porosity could lead to excessive spalling. The Ni-Cr/Al system also retained about the same thickness of MAl (160 to 300 μm) as did the others. Furthermore, it was believed that, as the MAl layer was depleted in Al, the Ni-Cr/Al system would develop a Ni-Cr-Al alloy layer beneath the oxide. Such alloys also exhibit good oxidation resistance.

here) was intermediate between coated and uncoated 304 stainless steel. No microstructural studies have yet been made since the tests are still in progress. Thus, from the limited testing and data available to date, the Ni-Cr/Al coating on 304 stainless steel appears to have promising oxidation resistance for automotive thermal reactor applications. In addition, this system would consume only a relatively low amount of strategic nickel as shown in the appendix.

CONCLUSIONS

Cyclic furnace oxidation tests were performed on 304 stainless steel and low carbon steel coated with an aluminum diffusion coating, two (one and two-step) chromium-aluminum coatings, a flame sprayed nickel-aluminum and aluminum diffusion coating, and a flame sprayed nickel-chromium and aluminum diffusion coating. Furnace test conditions ranged from up to 100 hours at 2000° F (1366 K) to 600 hours at 1800° F (1255 K). The furnace tests exposure cycles were 20 hours long. Preliminary automotive thermal reactor tests have also been conducted with cycles being 10 minutes at peak temperatures of 1900° F (1311 K) and 5 minutes at 1200° F (922 K) with intermediate cooldowns for inspection and weighing. The following conclusions can be drawn from the results of these tests and the subsequent metallurgical and X-ray diffraction analyses:

1. The most promising coating on 304 stainless steel was flame sprayed nickel-chromium followed by aluminum diffusion coating (Ni-Cr/Al). This coating provided good oxidation protection for 304 stainless steel during 600 hours of cyclic testing at 1800° F (1255 K) gaining only 3.5 milligrams per square centimeter during testing. Limited cyclic thermal reactor testing (166 cycles) of the Ni-Cr/Al coating on 304 stainless steel shows this system to have promising oxidation resistance for possible use in thermal reactor applications.

2. Based on a desired life of 2000 hours at operating temperatures to 1900° F (1038° C) with over-shoot capability to 2300° F (1260° C), the possibility of using low carbon steel materials, even with coatings, does not appear promising. The best system tested lost more than 35 mg/cm^2 in 40 hours (2 cycles) at 2000° F (1366 K). However, in the Ni-Cr/Al coated stainless steel system (or any coated metal system) reactor design must control the maximum metal temperature to assure the desired component life.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 13, 1970,
129-03.

APPENDIX - NICKEL CONSUMPTION

The consumption of nickel, a critical and strategic material, must be considered when contemplating the use of nickel containing alloys and coatings in thermal reactors for the annual production of approximately 10 million automobiles. Table III shows the cost per pound and approximate number of pounds of nickel that would be consumed, based on 15 million reactors for Inco 601, a good oxidation resistant alloy; Inco 800, a good candidate material when aluminum coated; and either 19-9 DL, a solid solution strengthened stainless steel or 304 stainless steel coated with the NiCr/Al system. Also shown in table III is the relative percent that this amount of nickel would be of the annual total nickel consumed in the United States based on 1967 data (ref. 4). Based on nickel consumption alone, 19-9 DL and 304 stainless steels appear to be comparable. However, as shown in table III, 19-9 DL costs approximately twice as much as 304 stainless steel. If the latter possesses suitable mechanical properties for reactor purposes, the use of NiCr/Al coated 304 stainless steel could be one way to conserve nickel and perhaps lower reactor costs.

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TABLE I. - SUMMARY OF COATING DEPOSITION ON LOW CARBON STEEL AND 304 STAINLESS STEEL

Coating	Low carbon steel		304 stainless steel	
	Average weight gain due to coating, mg/cm^2	Major phases in coating	Average weight gain due to coating, mg/cm^2	Major phases in coating
Al	16.63	Fe_2Al_5	14.78	Cr_3Al_2
Al, Cr	6.18	Cr or Fe (Al_2O_3)[a]	5.79	Cr or Fe (Al_2O_3)
Cr + Al	Cr 2.65 Al 14.10	Cr_2Al	Cr 1.17 Al 13.25	Cr_2Al (Cr_3Al_5, Cr_5Al_8)
Ni-Al/Al	NiAl 25.95 Al 12.02	Ni_2Al_3 (NiAl, FeAl)	NiAl 18.27 Al 12.95	Ni_2Al_3 (NiAl, Ni_3Al)
Ni-Cr/Al	NiCr 15.02 Al 16.77	Ni_2Al_3	NiCr 9.05 Al 15.38	Ni_2Al_3 (NiAl or Cr, Ni)

[a]Parenthesis indicate minor or trace phase.

TABLE II. - SUMMARY OF COATING BEHAVIOR ON LOW CARBON STEEL AND 304 STAINLESS STEEL DURING OXIDATION TESTING AT 2000° F (1366 K) AND 1800° F (1255 K)

Coating	Low carbon steel[a] after 40 hours (2 cycles) at 2000° F (1366 K). Weight change, mg/cm^2	304 stainless steel			
		After 100 hr (5 cycles) at 2000° F (1366 K)		After 600 hr (30 cycles) at 1800° F (1255 K)	
		Weight change, mg/cm^2	Phases present	Weight change, mg/cm^2	Phases present
Al	-37	-0.05	Al_2O_3 Spinel (a_o = 8.35 A) (Cr_2O_3)[a]	+1.5	Al_2O_3 Spinel (a_o = 8.30 A) (Cr_2O_3)
Al, Cr	[b]-79	[b]-1.0	Al_2O_3 Cr_2O_3 Spinel (a_o = 8.30 A) (Fe)	Not determined	Not determined
Cr + Al	-44	[c]-0.75	Al_2O_3 Spinel (a_o = 8.30 A) Martensite Austenite	-1.8	Al_2O_3 Spinel (a_o = 8.30 A) (Cr_2O_3)
Ni-Al/Al	-51	+0.5	Al_2O_3 NiAl	+2.8	Al_2O_3 (NiAl)
Ni-Cr/Al	-66	[c]+3.2	Al_2O_3 Spinel (a_o = 8.35 A)	+3.5	Al_2O_3 NiAl or Fe (MO where M is Ni, Cr or Fe)

[a]Parentheses indicate minor or trace phase.
[b]One cycle.
[c]Four cycles.

TABLE III. - ESTIMATED CONSUMPTION OF NICKEL BASED ON SEVERAL POTENTIAL THERMAL REACTOR CORE MATERIALS

Material[a]	Nickel content, percent	Mass of nickel in 15 million reactors		Percent of total nickel consumed in United States in 1967	Approximate cost of uncoated sheet	
		lbm	kg		$/lbm	$/kg
Inco 601	60	100.1×10^6	45.4×10^6	28.6	1.85	4.07
Inco 800	32	53.3	24.2	15.3	1.43	3.13
19-9 DL[b]	9	24.3	11.0	7.0	1.35	2.97
304[b]	8	22.5	10.2	6.5	.65	1.43

[a]Sheet thickness, 60 mils (1.5mm). Aproximately $4\frac{1}{2}$ ft^2 (0.42 m^2) are required for a typical thermal core reactor.

[b]Sheet is coated on both sides with Ni-Cr/Al.

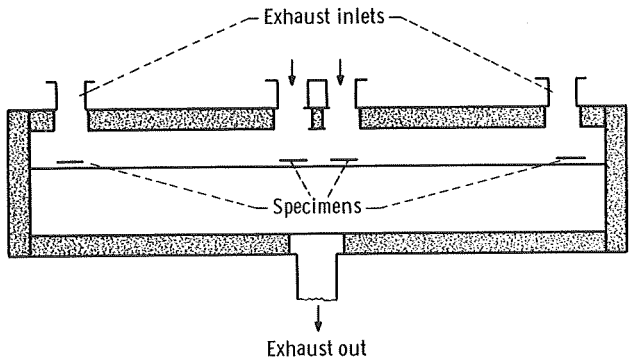
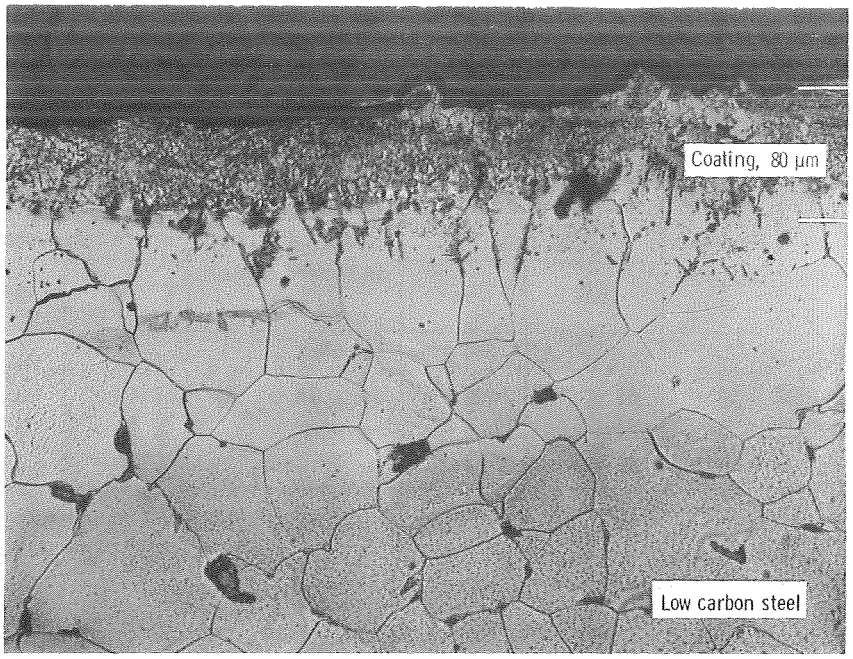
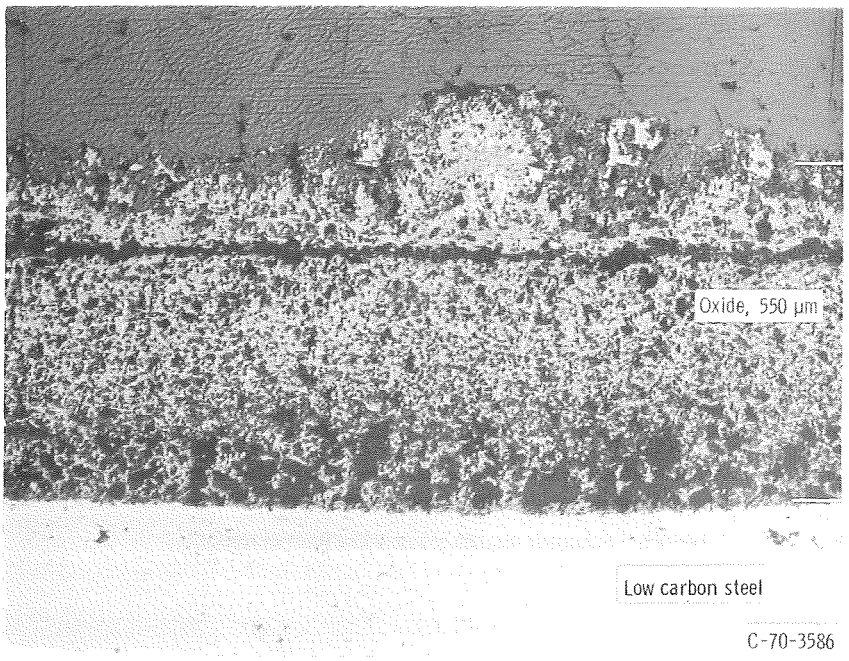


Figure 1. - Schematic diagram of automotive thermal reactor.

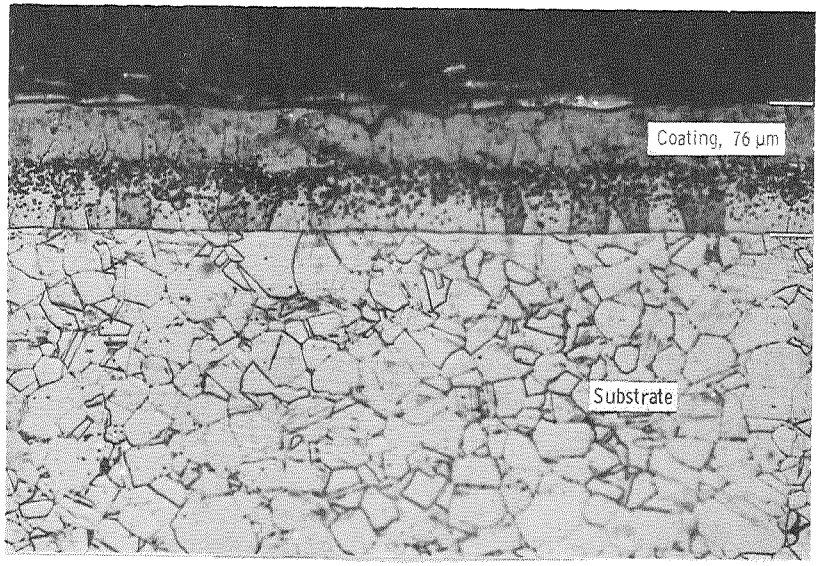


(a) As coated.

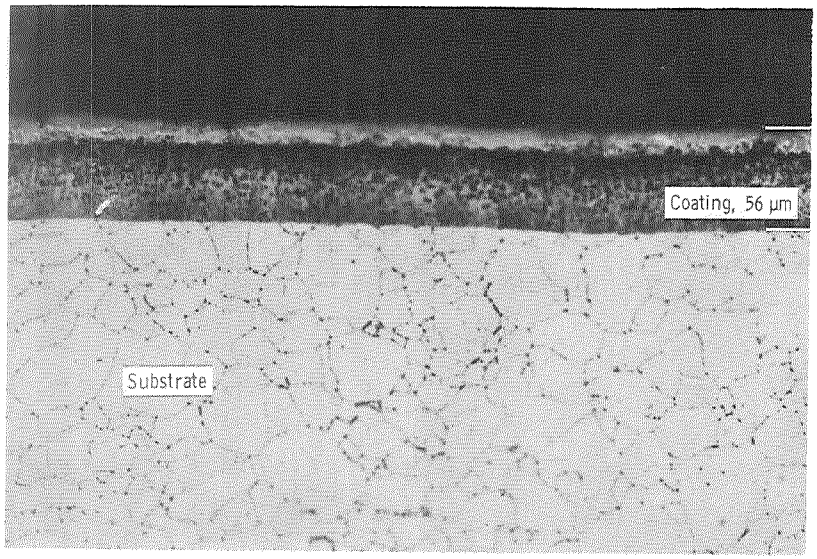


(b) After two 20-hour cycles at 2000° F (1366 K).

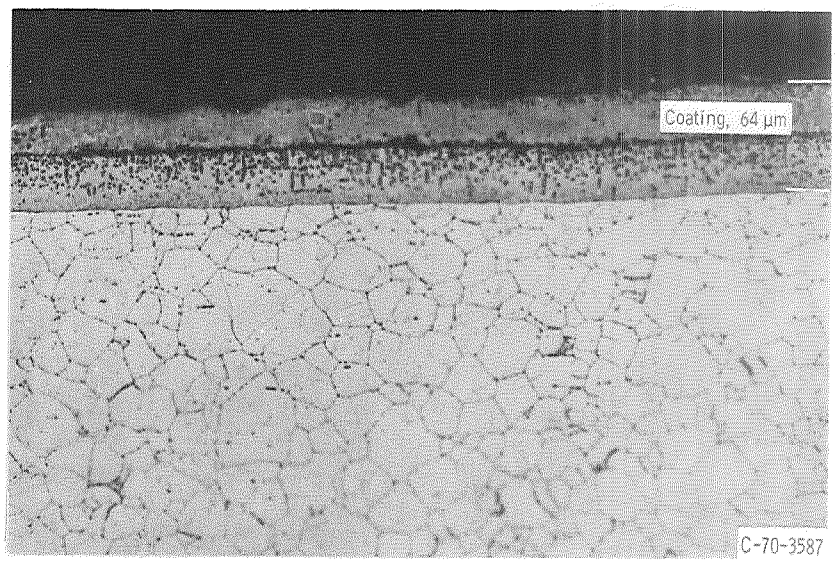
Figure 2. - Nickel-chromium/aluminum (Ni-Cr/Al) on low carbon steel in the as-coated condition.



(a-1) Aluminum diffusion coating (Al). X250.



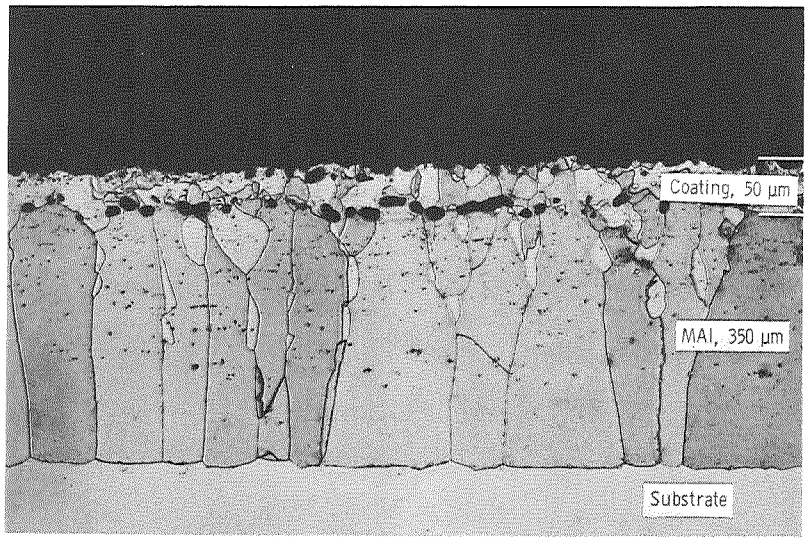
(a-2) One step aluminum chromium coating (Al, Cr). X250.



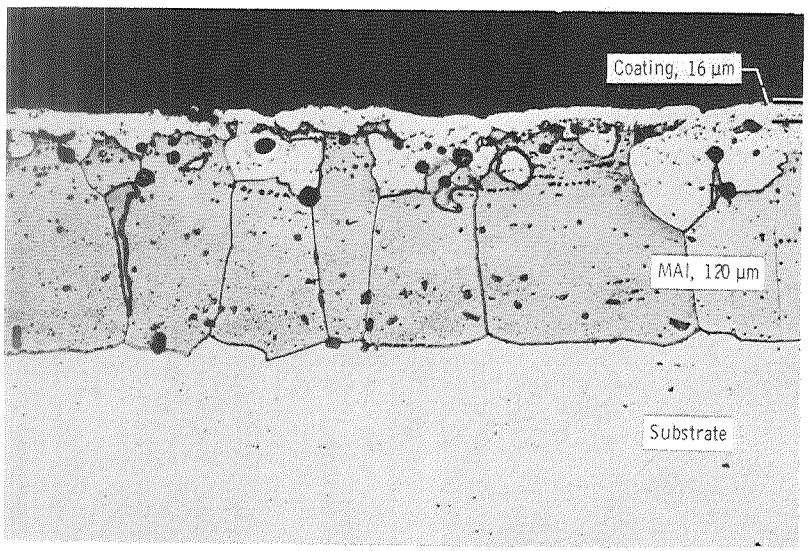
(a-3) Two step chromium then aluminum coating (Cr + Al). X250.

(a) As coated.

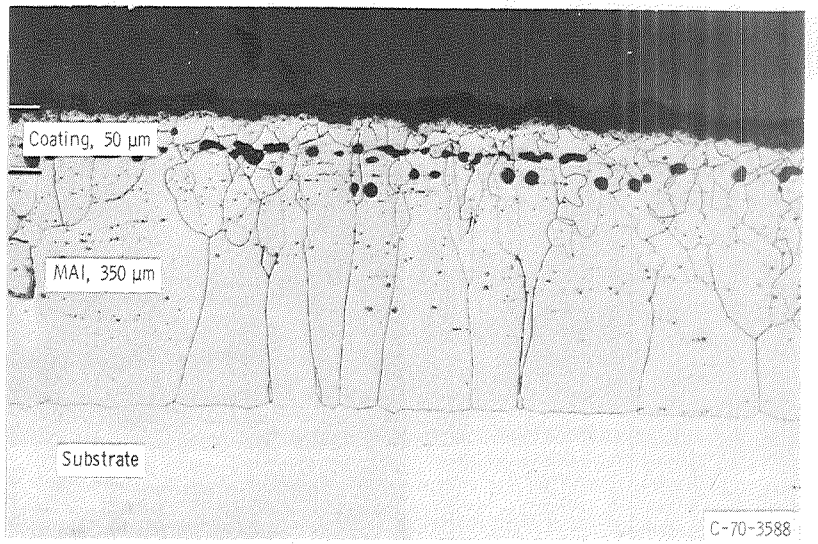
Figure 3. - Diffusion coatings on 304 stainless steel.



(b-1) Aluminum diffusion coating (Al) after five 20-hour cycles. X100.



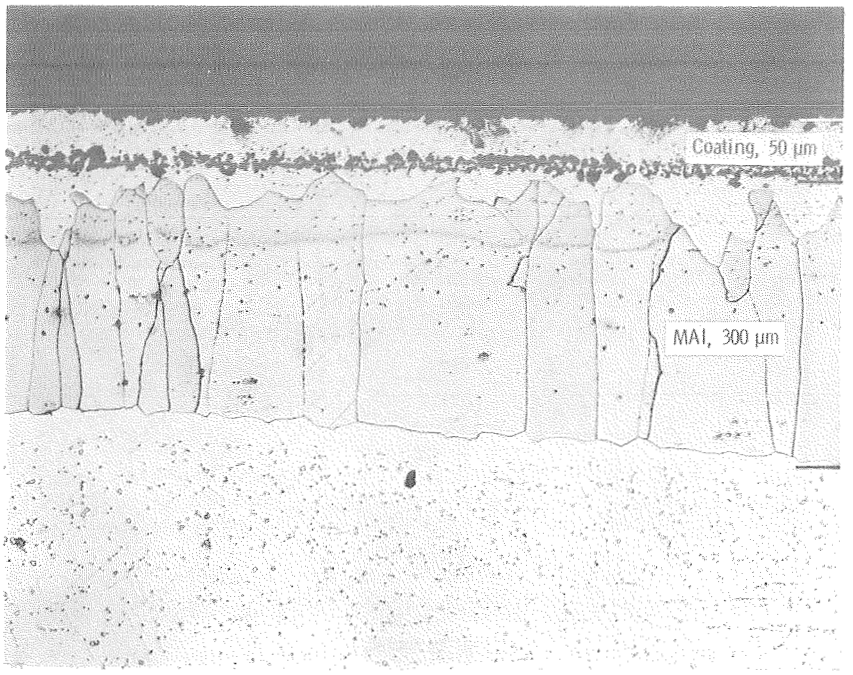
(b-2) One step aluminum-chromium coating (Al, Cr) after one 20-hour cycle. X250.



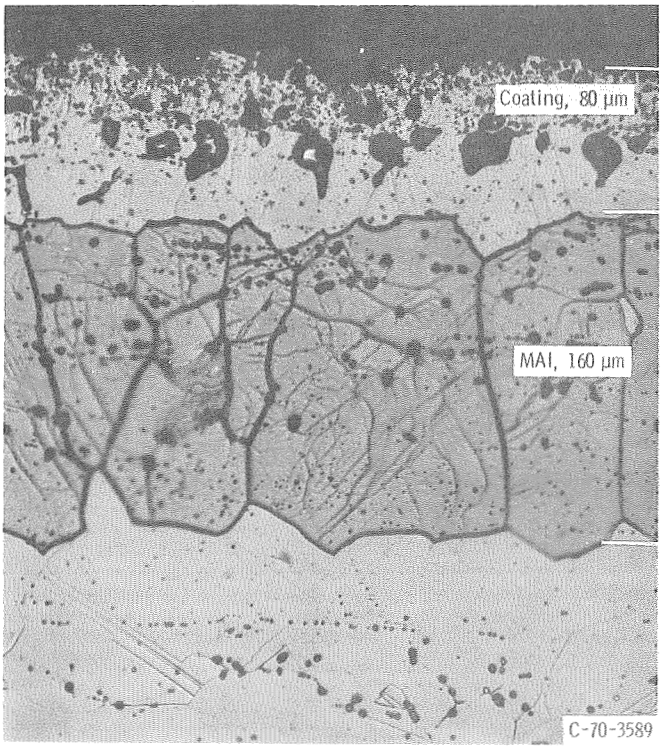
(b-3) Two step chromium then aluminum coating after four 20-hour cycles (Cr + Al). X100.

(b) After 2000° F (1366 K) testing.

Figure 3. - Continued.



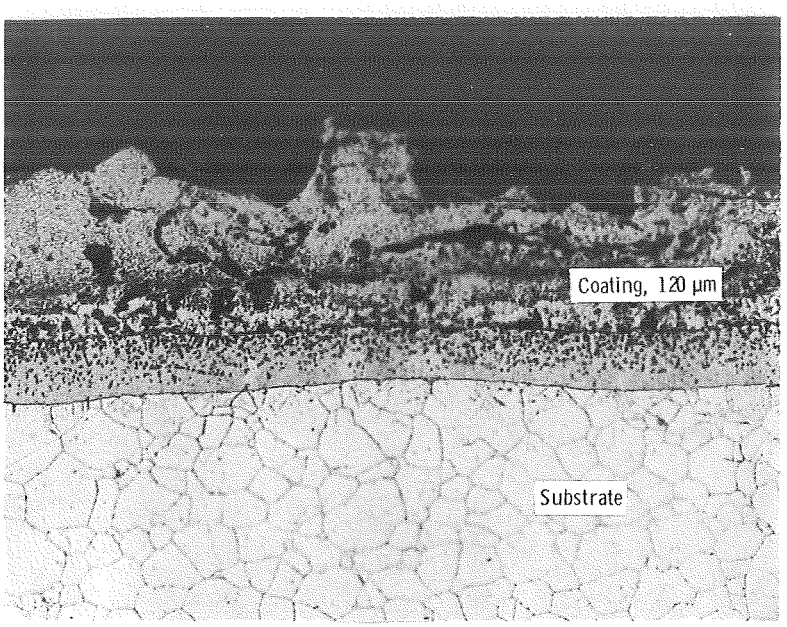
(c-1) Aluminum diffusion coating (Al). X100.



(c-2) Two step chromium then aluminum coating (Cr + Al). X250.

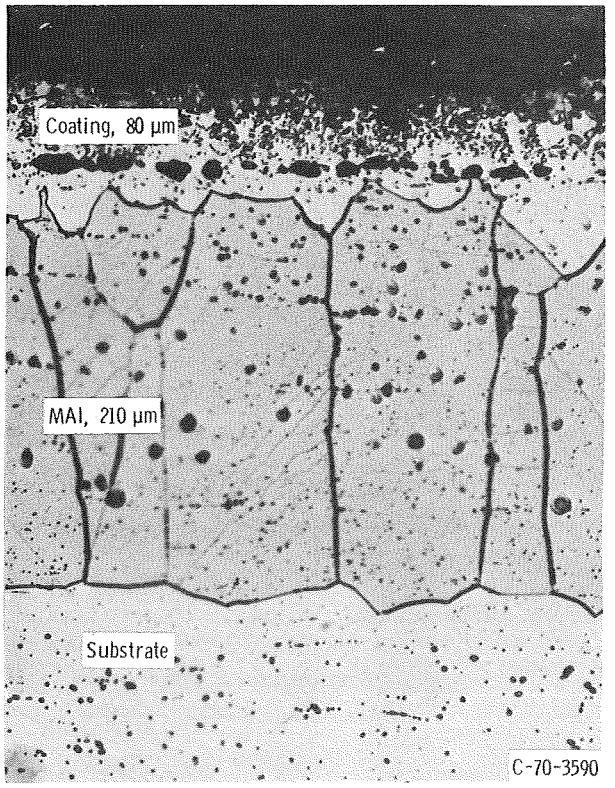
(c) After 600 hours at 1800° F (1255 K).

Figure 3. - Concluded.



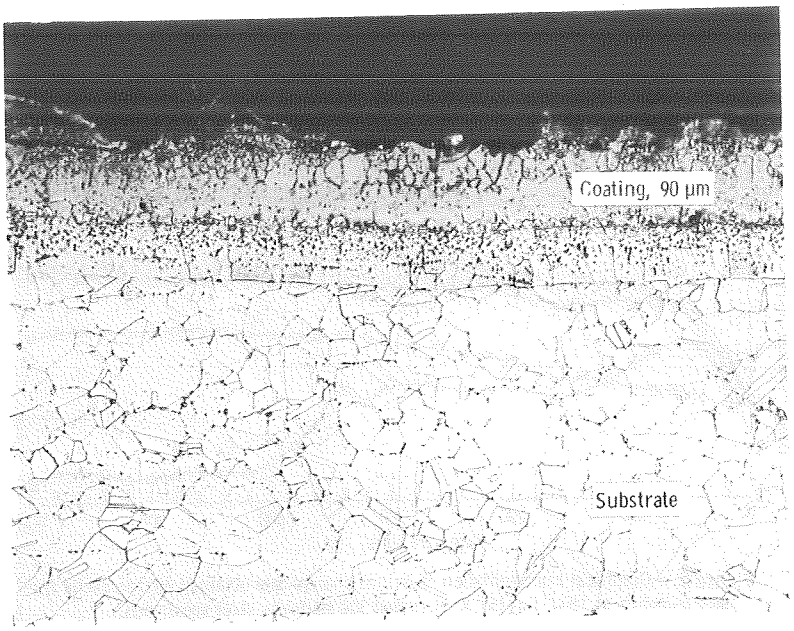
(a) As coated.

(b) Five 20-hour cycles at 2000° F (1366 K).

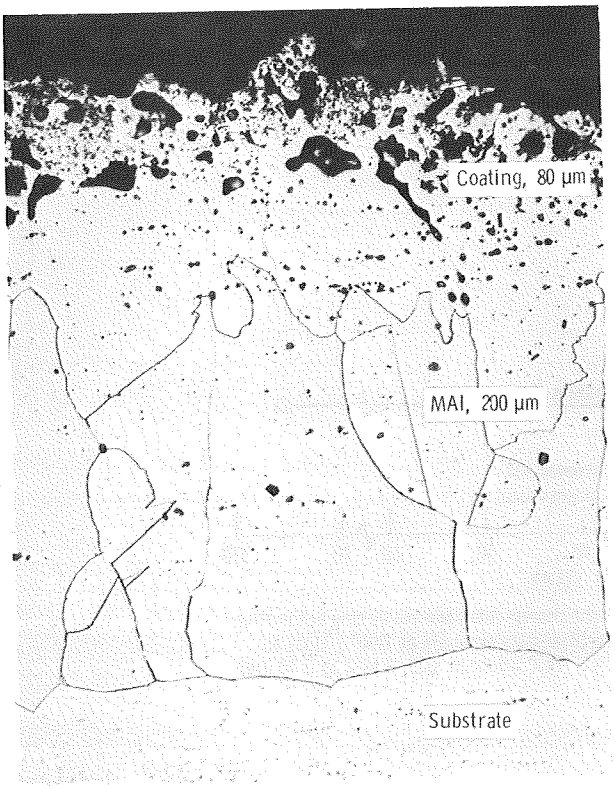


(c) Thirty 20-hour cycles at 1800° F (1255 K).

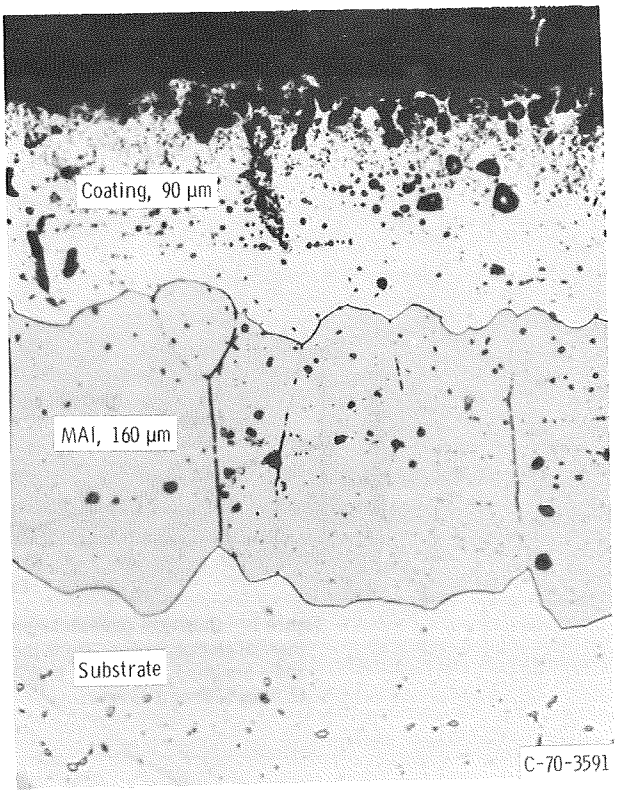
Figure 4. - Cross sectional photomicrograph of nickel-aluminum/aluminum stainless steel before and after oxidation testing. X250.



(a) As coated.



(b) Four 20-hour cycles at 2000° F (1366° K).



(c) Thirty 20-hour cycles at 1800° F (1255° K).

Figure 5. - Cross sectional photomicrographs of nickel-chromium/aluminum stainless steel before and after oxidation testing. X250.

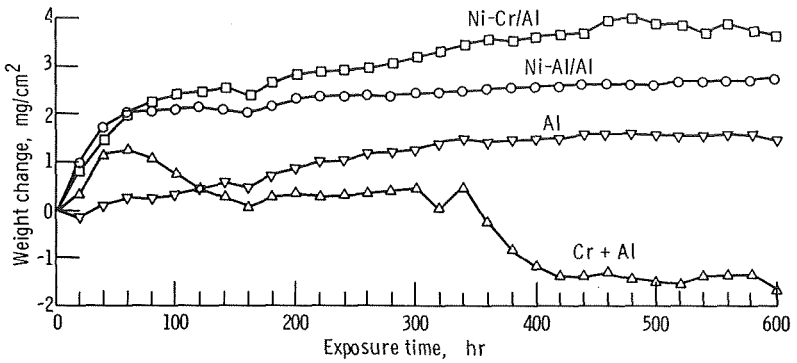


Figure 6. - Graphical representation of weight change data obtained during cyclic furnace oxidation at 1800° F (1155°K) of coated 304 stainless steel specimens.

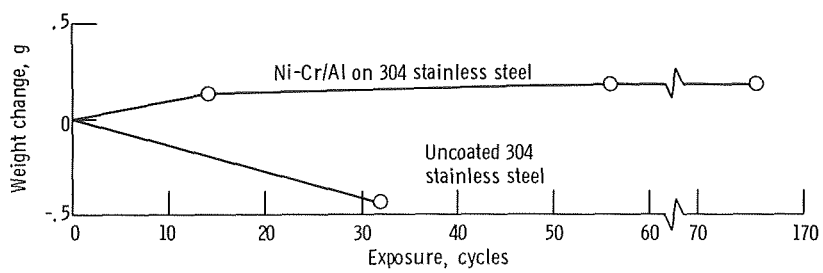


Figure 7. - Graphical representation of weight change data obtained during automotive thermal reactor testing. Cycle included a 10-minute exposure at 1900° F (1311 K) and a 5-minute exposure at 1200° F (922 K). Test specimen size, 1 by 2 by 0.60 inch (2.54 by 5.08 by 0.15 cm).

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